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Original Article

Biomechanical model based evaluation of Total Hip Arthroplasty therapy outcome

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ABSTRACT

Objective: Total-hip-arthroplasties are performed to treat patients with osteoarthritis. Surgical planning is usually based on specific radiographs. These information could also be used as data for biomechanical modelling.

Methods: Models are rarely used during clinical practice. Our aim was to analyze model-based the pre- and postoperatively hip-biomechanic. Pre- and postoperative X-rays of 30 patients were examined by using 4 biomechanical-models.

Results: The received results showed variations e.g. an increase and decrease of hip-load pre- and postoperative.

Conclusion: With the data of these models it would be possible to integrate the amplitude and orientation of the hip-joint-resultant-force into the therapeutical approach.

1. Introduction

Total Hip Arthroplasty (THA) is an established and effective treatment for osteoarthritis (OA). In Germany there are more than 215,000 THA interventions per year (in 2014) carried out, and more than 36,000 secondary revision interventions per year were performed [1]. Furthermore, THA has been performed on a large number of patients worldwide. It is among the most frequently executed orthopaedic operations, and is an increasingly common and successful operation of the last decades [2–4]. Today the average lifetime of a hip prosthesis is approximately 15 years [5,6].

In THA an accurate alignment and exact positioning of the hip prosthesis is a major factor affecting the longevity of a hip implant [7,8]. The hip joint is one of the most important weight-bearing joints in the human body, and it has an important biomechanical function: it enables a physiological bi-pedal gait and mobility, respectively, for a lifetime. During daily routine activities, forces up to 8 times body-weight (BW) (during stumbling) are transferred between the femoral head and the acetabulum [9]. Abnormal repetitive loading of the hip joint results in the breakdown of articular cartilage, thereby, destroying the normal function of the joint [10].

Postoperative complications after THA are dependent on multiple factors. Dislocation [6,11] and abrasion behavior of the prosthesis components [6,12] are one of the most common postoperative complications.

Musculoskeletal loading plays an important role in the primary stability of THA. Thus; simulation of the pre- and post-operative magnitude of the resultant hip joint force R is of interest to analyze hip biomechanics after THA. Biomechanical models can be used to get an impression about the patient specific intervention outcome. Simple 2D-models (e.g. Pauwels [13–15], Debrunner [16], Blumentritt [17,18]) and more complex 3D-models (e.g. Iglič et al., [19]), are available for estimation of the magnitude and the orientation of R depending on their geometrical and anthropometrical parameters.

For a successful THA it is essential to consider biomechanical factors in the anatomical features of the hip. During THA surgery, a couple of (biomechanical relevant) geometrical parameters influence the specific (biomechanical) operation outcome e.g. position of the hip rotational centrum (HRC), angle (inclination and anteversion) of the acetabular cup, caput-collum-diaphyseal angle of the hip stem (CCD-angle and neck angle, respectively), femoral offset and lever arms. Consequently, the positioning of the HRC influences the local loading situation at the implant–implant interface (head and cup) and the bone interface. For example, a slightly superior, posterior and medial HRC after total hip replacement can be associated with markedly higher joint forces [20].

Furthermore, the orientation and position of the acetabular cup is an important factor for satisfactory long-term results after THA [21]. Correct implantation of the THA is crucial with respect to long-term results and survival rate [22]. This is the reason why consideration of biomechanical aspects during THA is recommendable, and allows a high accuracy especially in cases with anatomical variations such as hip dysplasia and coxa valga/vara.

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Radiographs and clinical examination are the most important tools for the indication and follow up evaluation of THA [23]. It is possible to use the radiographs also to acquire anatomical/geometrical parameters for the biomechanical modelling. A preoperative planning and a post-operative examination of the therapy outcome e.g. of implant position under biomechanical aspects based on radiographs can be of enormous helpful for the surgeon [7].

We wanted to show how helpful the use of a biomechanical model could be. In our case, we used the mathematical models for a retospective analysation of THA therapy outcome. The objective of this study was in general the investigation of the resulting hip joint force R and their orientation calculated by the mathematical models of Pauwels, Blumentritt, Debrunner and Iglič. Then the differences between pre- and postoperative joint load can be quantified, and the therapy outcome can be shown. In detail, we wanted to show, that a biomechanical model can be easily implemented in a clinical workflow for therapy planning and outcome analysation. The objective was the investigation and comparison of the postoperative restauration in regard to the preoperative situation. We wanted to proof, if the post-operative outcome (amplitude and orientation of R) is similar or better (ideal: amplitude of R decreased and orientation approximately perpendicular on the cup of R) to the preoperative situation.

Furthermore, we evaluated the models of Pauwels, Blumentritt, Debrunner and Iglič in the way that we compare the results to measurments of the Orthoload-database (www.orthoload.com) for the one leg stance. Mathematical assessments derived from the model computations will be directly compared to a generated reference basis of in-vivo measurements obtained from instrumented hip implants. Thus, it is possible to get an impression of the validity of the mathematical models.

2. State of the art

Musculoskeletal models of the lower limb are widely used to predict the resultant joint force R in the hip joint as an alternative to instrumented implants [24,25]. Simple analytical mathmatical models are applied to predict hip joint biomechanics, and therefore, use the equations of statics to solve for resultant joint reaction forces. The models are based on the angles and length measurements in planar one leg standing anterior-posterior (a.p.) X-ray images of the hip and pelvis, respectively.

Friedrich Pauwels developed a widely accepted computational 2D model of the human hip joint [13–15]. Pauwels assumed in his model that R acting on the femoral head is created by the partial BW (FG5 = total BW minus the weight-bearing leg), which acts medially to the hip joint and the force of the abductor muscles (FM_P) inserting at the greater trochanter. R directly acts through the HRC, which approximately corresponds to the centrum of the femoral head. Pauwels pointed out that a normal hip equilibrium is achieved, when the BW is balanced by the force of the abductors. Pauwels' model is focusing on the one-leg stance.

Debrunner developed a modified model for the calculation of R of the human hip joint [16]. He adopted the basic idea of Pauwels' model. In his one-leg stance model, he also assumed that R, acting on the head of the supporting femur, is created by the partial BW and the force of the abductor muscles. In contrast to Pauwels, Debrunner proposed a different approach towards the modelling of the origin point of the abductor muscle or the computation of the partial BW. However, both model approaches of Pauwels and Debrunner are very similar.

Blumentritt analyzed the mechanical loading of the hip joint based on a more detailed coxometric study for the individual adaptation of a generic biomechanical model [17,18]. The calculation of the magnitude and the direction of R is based also on the equilibrium momentum by the pelvi-trochanteric muscle group, the spino-crural muscle group and the partial BW with an additional dynamic force. It is also basis for the Babisch-Layher-Blumentritt score (BLB-score), a biomechanical evaluation score for the position of the hip rotational center pre- and postoperatively during a THA. The idea behind the BLB-score is to describe the biomechanical situation of a hip joint by means of suitable biomechanical parameters. These biomechanical parameters are then compared to 6 reference values and evaluated according to their deviation from the reference values with 0 to 2 points (maximum of 12 points ($= 6 \cdot 2$ points) in sum is the best reachable outcome of the BLB-score). In the end, a total BLB-score is computed, which is taken as measure for the biomechanical condition of the hip joint [17,18,26–28].

Iglič developed a static three-dimensional model of the hip in order to evaluate the magnitude of R before and after a Chiari osteotomy [19]. Like many other hip models, including Pauwels' hip model, the purpose of Iglič̌s model is to estimate the effects of different orthopaedic interventions (here especially the chiari osteotomy), and to evaluate the biomechanical status of the hip with different femoral geometries. R is determined by solving the equilibrium equations for forces and torques in the one-leg stance based on the individual measurements of the femoral and pelvic geometry. The pelvis segment bears the partial BW (W_B-W_L) ($=F_{G5}$), where W_B is the total BW and W_L is the weight of the loaded leg.

In THA, the CCD-angle (Fig. 3A) and the femoral offset (Fig. 3B) need to be determined preoperatively during surgery planning and also for the selection of the implant. The CCD-angle is the projection of the angle between diaphysis and the femoral neck. The femoral offset is the distance from the center of rotation of the femoral head to a line dissecting the long axis of the femur [29]. In case of THA, a decrease in femoral offset would move the femur closer to the pelvis medially. This can lead to impingement of greater trochanter in extreme positions. An increase in femoral offset and of the lever arm of the abductor muscles, respectivelly, will also, theoretically, increase the mechanical advantage and strength of the abductors [29]. In case of a medial movement of the femoral prosthesis component this would result in soft tissue relaxation with the possibility of a joint instability and a possible dislocation. Moreover, when the offset decreases, greater force is required by the abductor muscles to balance the pelvis and resultant force across the hip joint also increases resulting in greater wear and tear. An increase in femoral offset decreases the force required by the abductor muscles to balance the pelvis. This fact leads to a decreasing of the resultant force, which may result in less wear and loosening over time. There is a strong correlation between femoral offset, abductors lever arm and hip abductor strength. Therefore, restoration of the femoral offset is essential to improve function and longevity of a THA. Finally, a larger femoral offset will increase stability by preventing impingement and improving soft tissue tension [29].

In THA, the inclination angle of the cup plays also an very important role. The inclination displays the angle between the face of the cup and a transverse axis [30] (Fig. 1). Cup positioning remains one of the biggest challenges in THA. The ideal cup inclination angle should be approximately 45° but is also described differently [7]. Current clinical results and computed simulations indicate an ideal acetabular cup position at 35–55°of inclination [7,12,21,31,32].

From a mechanical point of view the angle ϑ (Fig. 1A) between R and the cup inclination should be approximately 90°. R should be applied approximately central to the cup. In this situation the applied load to the cup is approximately optimal under mechanical aspects [12,34,35].

Implants with an internal sensor system (intrumented prothesis) are another possibility to acquire accurately information about hip loading post-operatively [9,36,37] (Fig. 1 B). In-vivo measurements with an instrumented prosthesis showed that dynamic hip joint forces lie in a similar range to those calculated by Pauwels [13–15] with his static computational model approach [38,39]. Instrumented implants potentially offer the most accurate information about the applied hip forces since assumptions inherent in all mathematical models can be eliminated and many activities can be studied [40,41]. The OrthoLoad-